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A Statistical Description of an Ionospheric Channel

by

M. R. Epstein

July 1967

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Technical Report No. 142

Prepared under
Office of Naval Research Contract
Nonr-225(64), NR 088 019, and
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RADIOSCIENCE LABORATORY
STANFORD ELECTRONICS LABORATORIES
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A STATISTICAL DESCRIPTION OF AN IONOSPHERIC CHANNEL

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RadioScience Laboratory

Stanford Electronics Laboratories

Stanford University Stanford, California

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ABSTRACT

An experimental procedure to determine ionospheric-channel amplitude and phase statistics as a function of time and frequency is described. A coherent-phase FM-CW sounder is programmed to sweep repetitively and rapidly (relative to ionospheric changes) a portion of the HF spectrum. The IF signal obtained by mixing the received signal with a replica of the transmitted signal possesses the amplitude and phase characteristics of the channel. These two characteristics are determined and subsequently analyzed by digital computer.

Computer correlations were performed on signals received at Stanford, California, over a one-hop, lower-ray path from Lubbock, Texas, during 485 successive 16- to 16.5-MHz sweeps (one sweep each 0.5 s) of an FM-CW sounder. The test was performed under winter-noon conditions. The ionospheric amplitude vs frequency characteristic decorrelated to a value of $1/e$ in 3 s and 70 kHz. These values are probably set by received-signal polarization changes.

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I INTRODUCTION

The purpose of this report is to describe a measurement technique for determining ionospheric-channel amplitude and phase statistics as a function of time and frequency. Knowledge of channel statistics is fundamental to the design of adaptive HF communication systems. Primary attention in this report is given to the amplitude statistics of the ionospheric channel, although the technique may also be employed to study phase-path statistics.

In this technique, a small portion of the HF spectrum is rapidly and repetitively swept by an FM-CW signal constant in amplitude and coherent in phase. The received signal, mixed with a frequency-translated replica of the transmitted signal to obtain an IF frequency, is then detected to produce an audio signal whose phase and amplitude are that of the ionospheric channel. This signal is analyzed by computer to determine statistical parameters, such as (1) the correlation of the signal amplitude and phase vs frequency, from sweep to sweep, providing information concerning ionospheric changes with time, and (2) autocorrelation of individual sweeps to provide "coherent" bandwidth data. The techniques and data reduction methods employed in the present experiment are described in Section II. The results of the analysis, and implications of the results for pulsed communication systems and the design of adaptive communications systems are discussed in Section III.

II EXPERIMENTAL EQUIPMENT AND DATA REDUCTION

A. EXPERIMENTAL ARRANGEMENTS

On 17 December 1966 at approximately 1900Z, an FM-CW sweep-frequency HF sounder¹ was employed to transmit 60 W from a horizontally polarized, log-periodic antenna at Lubbock, Texas, to a horizontal rhombic antenna situated at Stanford, California, a distance of 1900 km. Briefly, the sounding system consists of two similarly modified frequency synthesizers, one for transmitting and one for use as a receiver first mixer injection. The synthesizers generate a close approximation to a CW signal having a linearly increasing frequency. This is accomplished by rapid, coherent switching of the synthesizer frequencies in steps of 10 Hz. The resulting FM-CW signal was swept repetitively at a 1 MHz/s rate over the 16- to 16.5-MHz band, once each 0.5 s, as shown in Fig. 1.

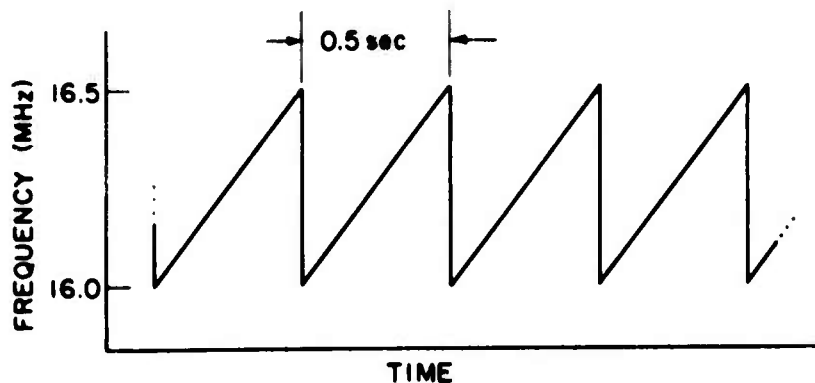


Fig. 1. TRANSMITTED WAVEFORM.

At the time of the experiment, signals in this frequency band traveled over the path by one-hop lower-ray mode, as demonstrated by the oblique ionogram shown in Fig. 2. The transmitted signal maintained a constant amplitude and a coherent phase across the spectrum. At the receiver, a fixed-frequency IF signal, obtained by mixing the received waveform with a replica of that transmitted, was product-detected in a communications receiver. The resulting audio signal, whose amplitude and phase correspond

to that of the one-hop lower ray ionospheric channel, was recorded on magnetic tape. Since a linearly increasing frequency sweep was employed, a given time on the tape corresponded to a given transmitted frequency.

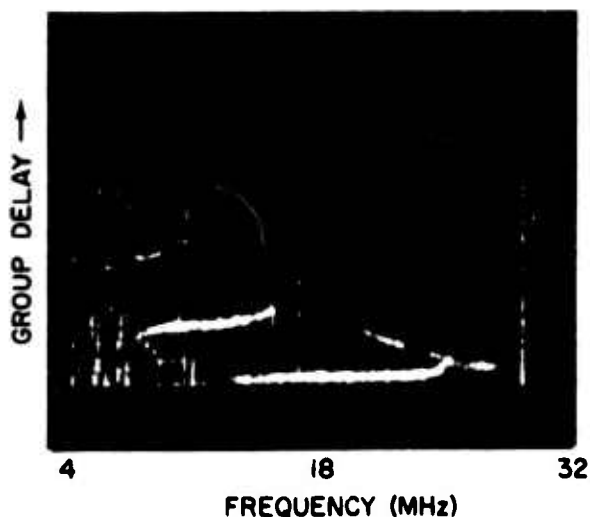


Fig. 2. OBLIQUE IONOGRAM MADE PRIOR TO EXPERIMENT.

A strip-chart of both the audio signal and its amplitude envelope was recorded for 485 of the half-second sweeps (a total recording time of 4 min, 2-1/2 s). Part of this record is shown in Fig. 3.

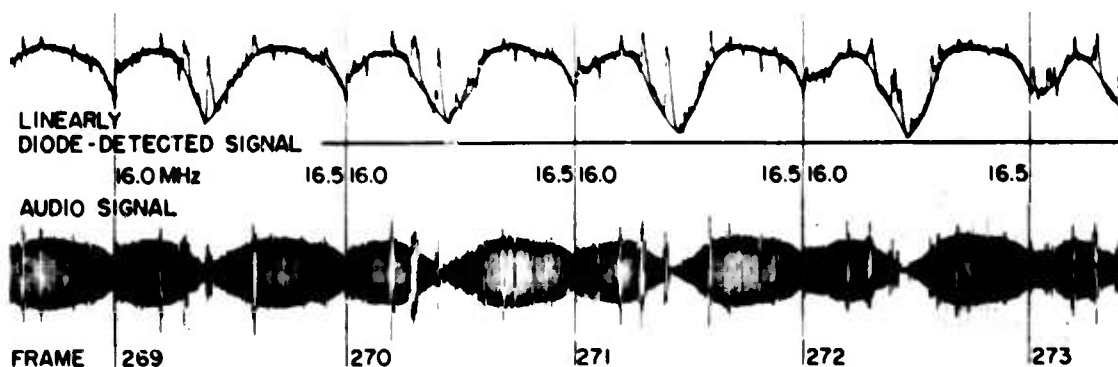


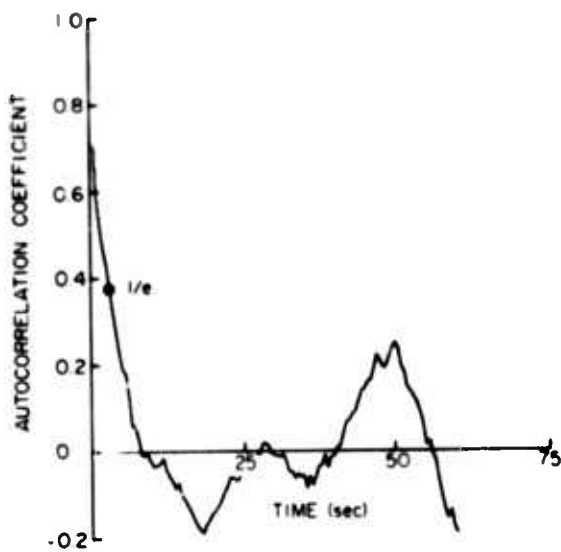
Fig. 3. STRIP-CHART RECORDING OF AMPLITUDE CHARACTERISTICS.

The amplitude curves on the charts were manually smoothed using the full-signal record as a guide to eliminate the effects of interference bursts that are produced whenever a fixed-frequency radio transmission is swept over. The result of this analysis is a continuous half-second sampling of the amplitude-vs-frequency characteristic of the ionospheric channel over a 500-kHz band.

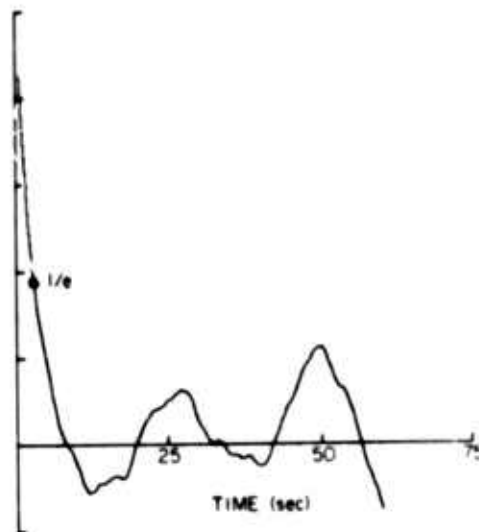
B. DATA REDUCTION

The amplitude strip-chart records were sampled 21 times per sweep (including endpoints) on a Benson Lehner Oscar K machine. This device produces punch cards on which the sweep number, sample number, and sample value appear. A 7090 computer was then employed to determine a statistical description of the ionospheric channel. Specifically, plots of average correlation coefficient vs time were made using both the full 500-kHz sweep, and 250-kHz, 125-kHz, and 50-kHz segments of the sweep, by correlating all possible adjacent, alternate, and more widely separated sweeps. A simple correlation average was then determined for each of the possible time spacings. The formulas employed in these computations are presented in the Appendix. The results, shown in Fig. 4, indicate the rapidity with which the amplitude-vs-frequency characteristic of the ionosphere changes with time. It can be seen that for all cases considered, the amplitude characteristic decorrelated to approximately $1/e$ in about 3 s.

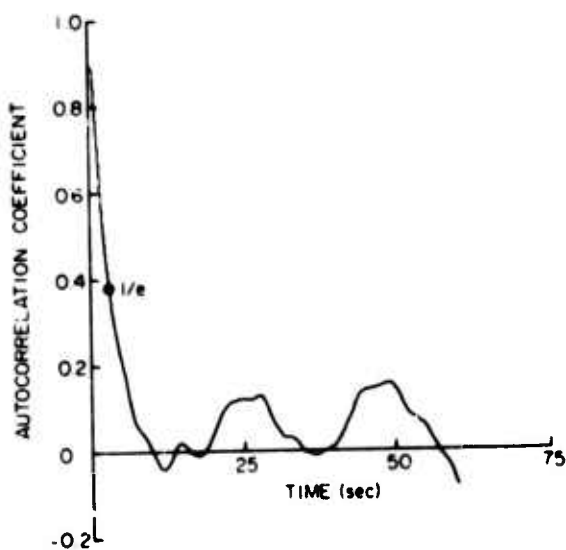
Computations to determine the average autocorrelation coefficient as a function of frequency were made using frequency segments from 50 kHz to 450 kHz. It is the nature of the autocorrelation function employed (see Appendix) that the largest number of autocorrelation values are obtained for the smallest frequency segment. The computer autocorrelated each of the sweeps and then determined a simple average. The results appear in Fig. 5. A "coherent" bandwidth, defined to be the band within which the autocorrelation coefficient is above $1/e$, may be determined from the limit of the size of the " $1/e$ bandwidths" as the frequency segments decrease in size. A curve to determine this is drawn in Fig. 6. It indicates that the average coherent amplitude bandwidth at 16.25 MHz was 70 kHz.



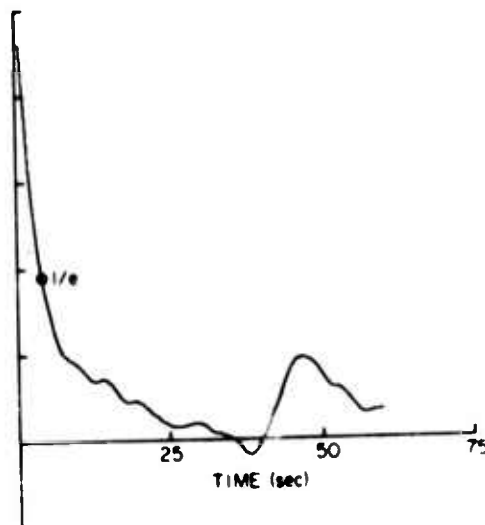
4a. 50 kHz Segment



4b. 125 kHz Segment

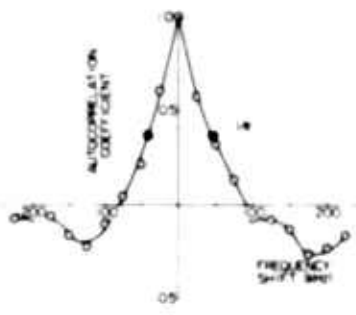


4c. 250 kHz Segment

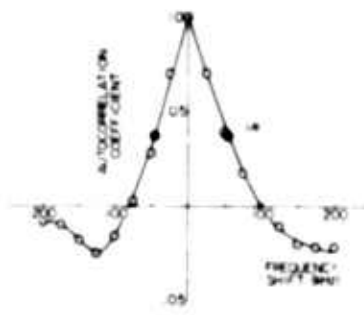


4d. 500 kHz Segment

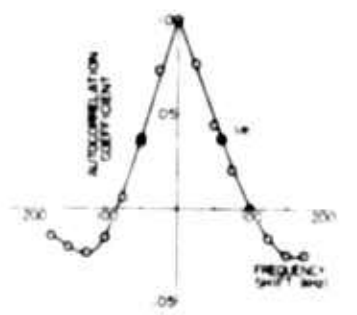
Fig. 4. AMPLITUDE CORRELATION AS A FUNCTION OF TIME.



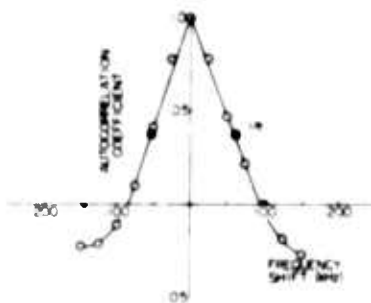
5a. 50 kHz Segment



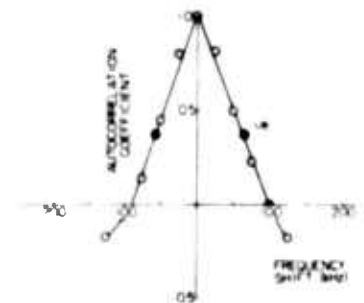
5b. 100 kHz Segment



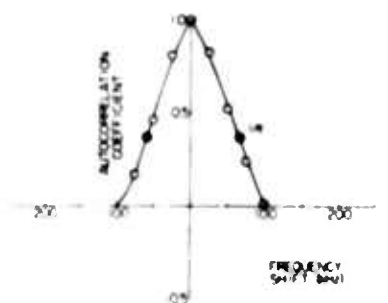
5c. 150 kHz Segment



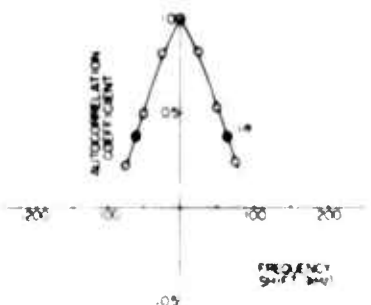
5d. 200 kHz Segment



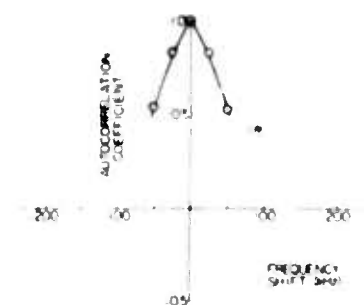
5e. 250 kHz Segment



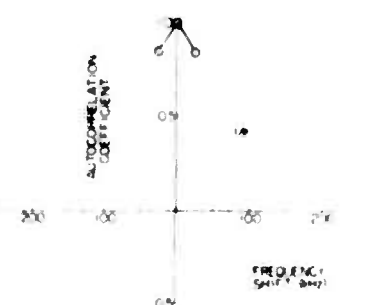
5f. 300 kHz Segment



5g. 350 kHz Segment



5h. 400 kHz Segment



5i. 450 kHz Segment

Fig. 5. AMPLITUDE AUTOCORRELATION AS A FUNCTION OF FREQUENCY.

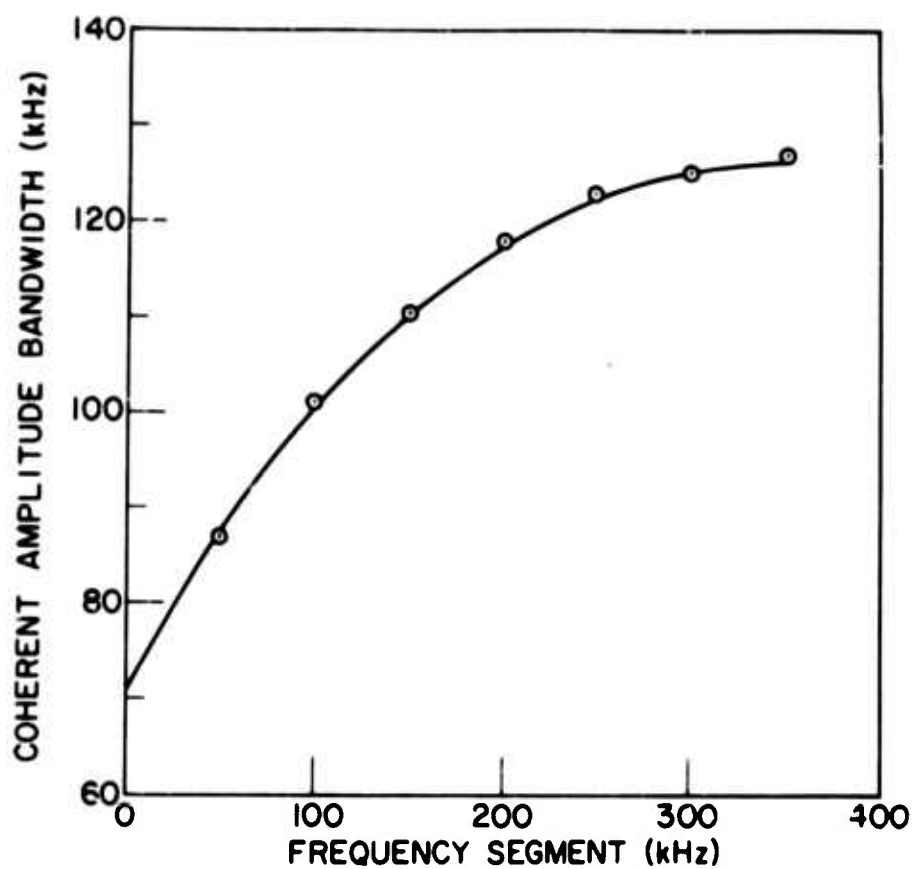


Fig. 6. AMPLITUDE AUTOCORRELATION BANDWIDTH VS FREQUENCY SEGMENT.

III DISCUSSION

It was noted earlier that both the transmitting and receiving antennas were nearly linearly polarized. Discussions in another report² have shown that polarization is the dominant factor in determining the instantaneous value of single-mode ionospheric channel amplitude, both as a function of frequency and time. The data presented in Section II indicate that the incoming lower-ray one-hop polarization rotated an average of a quarter-turn once every 10 s and 100 kHz (corresponding to the first null of the shorter-segment correlation curves). In the above cited report, it is indicated that regular variations in the amplitude-vs-frequency characteristic of the ionosphere such as that measured here determine a maximum pulsed signal bandwidth, beyond which envelope distortion will occur.

The measurements of Section II, which provide a measure of the rate with which the ionospheric channel changes, are fundamental to the design of adaptive devices intended to reduce the effects of ionospheric dispersion. The present results indicate that for an ionospheric dispersion equalization device which operates by dividing up the spectrum into equal segments, each segment possessing adjustable amplitude and phase, the desired spectrum segment would be about 70 kHz and the amplitude adjustments would have to be updated at approximately 3 s intervals.

IV CONCLUSIONS

This report has described a method for obtaining a statistical description of the amplitude and phase of an ionospheric channel. Such a description is fundamental to the design of adaptive HF communications systems. An FM-CW sounder, which transmits signals constant in amplitude and coherent in phase, is programmed to repetitively and rapidly sweep a portion of the HF spectrum. The received signal, which possesses the amplitude and phase characteristics of the ionospheric channel, is analyzed by digital computer.

Computer correlations were performed on received signals obtained by repetitively sweeping the transmitted signal of a 16 MHz FM-CW oblique-path sounder through a 500 kHz band, once every 0.5 s. It was found that, for the one-hop lower ray, the ionospheric amplitude-vs-frequency characteristic decorrelated to a value of $1/e$ in 3 s and 70 kHz. These values are probably set by received-signal polarization changes.

Appendix CORRELATION FORMULAS

TIME CORRELATION

Each of the 285 frames of data consists of 21 points. Thus, the i^{th} frame may be written as the set $\{X_{1,j}\}$, $j = 1, \dots, 21$.

$$\text{Let } \overline{X_{1,a,b}} = \frac{\sum_{j=\left[(b-1)\frac{20}{a}\right]+1}^{b\frac{20}{a}+1} X_{1,j}}{\frac{20}{a} + 1}$$

and,

$$r_{ab}(1,n) = \frac{\sum_{j=\left[(b-1)\frac{20}{a}\right]+1}^{b\frac{20}{a}+1} (X_{1,j} - \overline{X_{1,a,b}})(X_{1+n,j} - \overline{X_{1+n,a,b}})}{\sqrt{\sum_{j=\left[(b-1)\frac{20}{a}\right]+1}^{b\frac{20}{a}+1} (X_{1,j} - \overline{X_{1,a,b}})^2 \sum_{k=\left[(b-1)\frac{20}{a}\right]+1}^{b\frac{20}{a}+1} (X_{1+n,k} - \overline{X_{1+n,a,b}})^2}}$$

where the a and b indices are introduced to enable consideration of time segments within a frame. " a " is the number of divisions within a frame and " b " is the order number of each division. n is frame number, or time. Let

$$\overline{r_{ab}(n)} = \frac{\sum_{i=1}^{485-n} r_{ab}(i,n)}{(485-n)a}$$

The amplitude correlation vs time plots are graphs of $\overline{r_{ab}(n)}$ vs n for $a = 1, 2, 4, 10$, and $b = 1$.

FREQUENCY AUTOCORRELATION

Let

$$\overline{X_{1,d}} = \frac{\sum_{j=11-d}^{11+d} X_{1,j}}{2d+1}$$

$$\overline{X_{1,d,h}} = \frac{\sum_{j=11-d}^{11+d} X_{1,j+h}}{2d+1}$$

where $2d$ represents the frequency band about the center sample, and h represents the amount of waveform shift employed in the autocorrelation process. Then, let

$$f_{1,d}(h) = \frac{\sum_{j=11-d}^{11+d} (X_{1,j} - \overline{X_{1,d}}) (X_{1,j+h} - \overline{X_{1,d,h}})}{\sqrt{\sum_{j=11-d}^{11+d} (X_{1,j} - \overline{X_{1,d}})^2 \sum_{j=11-d}^{11+d} (X_{1,j+h} - \overline{X_{1,d,h}})^2}}$$

and

$$f_d(h) = \frac{\sum_{i=1}^{285} f_{1,d}(h)}{285}$$

The plots of amplitude autocorrelation vs frequency are graphs of $f_d(h)$ vs h for $d = 1, 2, \dots, 9$.

REFERENCES

1. R. B. Fenwick and G. H. Barry, "HF Measurements Using Extended Chirp-Radar Techniques," Report SU-SEL-65-058, TR No. 103, Contract Nonr-225(64), Stanford Electronics Laboratories, Stanford, Calif., June 1965.
2. M. R. Epstein, "Computer Prediction of the Effects of HF Oblique-Path Polarization Rotation with Frequency," Report SU-SEL-67-026, TR No. 139, Contract Nonr-225(64), Stanford Electronics Laboratories, Stanford, Calif., Feb. 1967.

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HF COMMUNICATIONS

IONOSPHERIC SOUNDING